

AMENDMENTS

- Please replace the specification and abstract filed herewith with the attached substitute specification and abstract.
- Please replace the drawings filed herewith with the attached substitute drawings.

REMARKS

The Specification:

Applicant has replaced the specification and abstract originally filed with the attached substitute specification and abstract in accordance with 37 C.F.R. § 1.125(b). The substitute specification and abstract do not contain any new matter. Both a marked-up copy and a clean copy incorporating the mark-ups are attached for the Examiner's review.

The Drawings:

Applicant has replaced the drawings originally filed with the attached drawings in accordance with 37 C.F.R. § 1.85. The drawings do not contain any new matter.

The Examiner is invited to contact the undersigned attorney at 713.787.1499 with any questions, comments or suggestions relating to the application.

Respectfully submitted,



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Serial No. 10/010,183

MARKED-UP COPY OF ORIGINAL SPECIFICATION AND ABSTRACT

3 (ADDED MATERIAL IS UNDERLINED,

4 DELETED MATERIAL IS STRICKEN THROUGH)

5

6 **FLUID DENSITY MEASUREMENT IN PIPES USING ACOUSTIC PRESSURES**

7

8 **CROSS REFERENCES TO RELATED APPLICATIONS**

9 This application contains subject matter related to that disclosed in commonly
10 owned co-pending USU.S. Patent Applications, Serial No., 09/344,094, entitled "Fluid
11 Parameter Measurement in Pipes Using Acoustic Pressures", Pressures." filed June 25,
12 1999,1999; Serial No. 09/344,070, entitled "Measurement of Propagating Acoustic
13 Waves in Compliant Pipes", Pipes." filed June 25, 1999,1999; Serial No. 09/344,069,
14 entitled "Displacement Based Pressure Sensor Measuring Unsteady Pressure in a
15 Pipe", Pipe." filed June 25, 1999,1999; and Serial No. 09/344,093, entitled "Non-Intrusive
16 Fiber Optic Pressure Sensor for Measuring Unsteady Pressures within a Pipe", Pipe." filed
17 June 25, 1999, all of which are incorporated herein by reference.

18

19

TECHNICAL FIELD

20 This invention relates to fluid parameter measurement in pipes and more
21 particularly to measuring speed of sound and density of fluids in pipes using acoustic
22 pressures. The measurement exploits the interaction between pipe flexibility, speed of
23 sound propagation, and density of the fluid within a conduit.

24

25

BACKGROUND ART

26 It is well known that by measuring the speed of sound a_{mix} of fluids in pipes may
27 be used to determine (a_{mix}) of a fluid in a pipe, various parameters of the fluid may be
28 determined, such as is described in USU.S. Patent No. 4,080,837, entitled "Sonic
29 Measurement of Flow Rate and Water Content of Oil-Water Streams", Streams." to
30 Alexander et al., USal.; U.S. Patent No. 5,115,670, entitled "Measurement of Fluid
31 Properties of Two-Phase Fluids Using an Ultrasonic Meter", to Shen, and USMeter," to

1 Shen; and U.S. Patent 4,114,439, entitled "Apparatus for Ultrasonically Measuring
2 Physical Parameters of Flowing Media",Media, to Fick. Such techniques haveutilize a
3 pair of acoustic transmitters/receivers (transceivers) thatto generate a sound signal and to
4 measure the time it takes for the sound signal to travel between the transceivers. This is
5 also known as a "sing-around" or "transit time" method. However, such techniques
6 require precise control of the acoustic source and are costly and/or complex to implement
7 in via electronics.

8 Also, these techniques use ultrasonic acoustic signals as the sound signals
9 measured, which are high frequency, short wavelength signals (i.e., wavelengths that are
10 short compared to the diameter of the pipe). Typical ultrasonic devices operate near 200k
11 Hz, which corresponds to a wavelength of about 0.3 inches in water. In general, to allow
12 for signal propagation through the fluid in an unimpeded and thus interpretable manner,
13 the fluid should be homogeneous down to ~~length scale~~scale lengths of several times
14 smaller than the acoustic signal wavelength. Thus, the criterion for homogeneity of the
15 fluid becomes increasingly more strict with shorter wavelength signals. Consequently,
16 inhomogeneities in the fluid, such as bubbles, gas, dirt, sand, slugs, stratification,
17 globules of liquid, and the like, will reflect or scatter the transmitted ultrasonic signal.
18 Such reflection and scattering inhibit the ability of the instrument to determine the
19 propagation velocity. For this reason, the application of ultrasonic flow_meters has been
20 limited primarily to well mixed flows.

21 Gamma-densitometers are widely used in the art for performing density
22 measurements of fluids within pipes. These devices utilize a nuclear source to expose the
23 fluids to a gamma radiation beam and measure density based on gamma beam absorption.
24 The primary drawbacks of this type of density meter are the environmental and safety
25 issues associated with the nuclear sources.

26 Another prior art method of determining the density of a fluid within a pipe is
27 through the use of a Coriolis meter. A Coriolis meter measures mass flow and density
28 as the primary measurements by tracking the natural frequency of a vibrating pipe filled
29 with the fluid. These devices require a vibration source, among other elements, which
30 make Coriolis meters mechanically complex, and relatively expensive to install and
31 maintain.

1

2 SUMMARY OF THE INVENTION

3 Objects of the present invention include provision of a system for measuring the
4 density of fluids in pipes.

5 According to the present invention, an apparatus for measuring the density of at
6 least one fluid in a pipe, comprisesing at least two sound speed meters, disposed at
7 different sensing regions along the pipe, and, each Each sound speed meter measuresing
8 an acoustic pressure within the pipe at a corresponding axial location, each of the sound
9 speed meters providing an system effective sound speed signal indicative of the
10 propagation velocity of a one-dimensional acoustic pressure wave traveling along the
11 pipe at each of the sound speed meters (a_{1eff} and a_{2eff}), at the sensing region of a
12 corresponding one of the sound speed meters and a A signal processor, responsive to the
13 sound speed signals, which provides a signal indicative of the density of the fluid in the
14 pipe.

15 According further to the present invention, the cross sectional compliance of the
16 two sensing regions is substantially different from one another. According still further to
17 the present invention, the compliance of the pipe is different in each of the two sensing
18 regions. In sStill further accord to the present invention, the cross sectional geometry of
19 the pipe is of a non-circular geometry in one of the two sensing regions.

20 According still further to the present invention, the sound speed meters are fiber
21 optic based sound speed meters. Still further in accord to the present invention, the
22 sound speed metersand are isolated from an outside environment by a concentric shell.
23 Further according to the present invention, tThe shell comprises an evacuated space, or is
24 filled with a fluid of known acoustic impedance.

25 The present invention provides a significant improvement over the prior art by
26 providing a measurement of the density ρ_{mix} of a mixture of one or more fluids within a
27 pipe (where a fluid is defined as a liquid or a gas) by using an axial array of sound speed
28 meters positioned along the pipe. An explicit acoustic noise source is not required, as the
29 background acoustic noises within the pipe (or fluid therein) will likely provide sufficient
30 excitation to enable characterization of the speed of sound of the mixture by merely
31 passive acoustic listening.

1 The invention works with acoustic signals having lower frequencies (and thus
2 longer wavelengths) than those used for ultrasonic meters, such as below about 20k Hz
3 (depending on pipe diameter). As such, the invention is more tolerant to the introduction
4 of gas, sand, slugs, or other inhomogeneities in the flow.

5 The present invention allows the density to be determined in a pipe independent
6 of pipe orientation, i.e., vertical, horizontal, or any orientation therebetween. Also, the
7 invention does not require any disruption to the flow within the pipe (e.g., an orifice or
8 venturi). Furthermore, if ~~harsh environment~~ fiber optic sound speed meters are used to
9 obtain the effective system sound speed measurements, which are well suited to the harsh
10 down hole environment, such meters eliminate the need for any electronic components
11 down-hole, thereby improving reliability of the measurement.

12 Also, a strain gauge (optical, electrical, etc.) based sound speed meter that
13 measures hoop strain on the pipe may be used to measure the ac pressure. Fiber optic
14 wrapped sensors may be used as optical strain gauges to provide circumferentially
15 averaged pressure. Thus, the present invention provides non-intrusive measurements of
16 the density of the fluid, which enables real time monitoring and optimization for oil and
17 gas exploration and production.

18 The foregoing and other objects, features, and advantages of the present invention
19 will become more apparent in light of the following detailed description of exemplary
20 embodiments thereof.

21

22 **BRIEF DESCRIPTION OF THE DRAWINGS**

23 Fig. 1 is a schematic block diagram of a density meter system, in accordance with
24 the present invention.

25 Fig. 2 is a graphical representation of the effective system speed of sound of a
26 fluid/pipeline system for various pipe wall thicknesses, in accordance with the present
27 invention.

28 Fig. 3 is a graphical representation of the change in effective system speed of
29 sound of a fluid/pipeline system for various fluid compliances, in accordance with the present
30 invention.

1 Fig. 4 is a schematic block diagram of a density metersystem having an egg
2 shaped cross section in one sensing region, in accordance with the present invention.

3 Fig. 5 is a cross sectional representation of an embodiment of a density meter
4 having a closed cell foam liner, in accordance with the present invention.

5 Fig. 6 is a schematic block diagram of a density metersystem having a tube
6 positioned within the flow path, in accordance with the present invention.

7 Fig. 7 is a graphical representation of the effectivesystem speed of sound of a
8 fluid/pipe system for various volume fractions of a brine/oil mixture, in accordance with
9 the present invention.

10 Fig. 8 is a schematic block diagram of a density metersystem having an input tube
11 positioned between the sensing regions, in accordance with the present invention.

12 Fig. 9 is a graphical representation of the effectivesystem speed of sound of a
13 fluid/pipe system for various volume fractions of a gas/fluid mixture, in accordance with
14 the present invention.

15

16 **BEST MODE FOR CARRYING OUT THE INVENTION DETAILED**
17 **DESCRIPTION OF THE INVENTION**

18 Density meter 1 in Fig. 1 using The density meter 1 of Fig. 1 uses a pair of sound
19 speed meters 14, 16 placed at axial locations, or sensing regions, X₁, X₂ along the pipe
20 12, measures, 12 for measuring the density of at least one fluid in a pipe 12. The sound
21 speed meters 14, 16 provide the effective speed of sound $a_{1\text{eff}}$ and $a_{2\text{eff}}$ of the fluid/pipe
22 system on lines 20, 22 which are provided to signal processing logic 60 which determines
23 the density of the fluid (or mixture) in the pipe 12 using relationships between the
24 compliance of the pipe and various fluid parameters as will be more fully described herein
25 below. Numerous sensing and processing techniques may be employed to further
26 determine the infinite speed of sound a_{mix} of fluid and fluid/pipe system
27 the fluid in the fluid/pipe system from the measured effective speed of sound a_{eff} , such as
28 those disclosed in ~~commonly owned copending U.S.~~ Patent Application Serial No.
29 09/344,094, entitled "Fluid Parameter Measurement in Pipes Using Acoustic Pressures,"
30 filed June 25, 1999, the disclosure of which is incorporated herein by reference in its
31 entirety.

1 Also, ~~some~~Some or all of the functions within the logic 60 may be implemented
2 in software (using a microprocessor or computer) and/or firmware, or may be
3 implemented using analog and/or digital hardware, having sufficient memory, interfaces,
4 and capacity to perform the functions described ~~herein~~.

5 The effective speeds of sound $a_{1\text{eff}}$ and $a_{2\text{eff}}$ are provided to logic 60 wherein the
6 logic calculates the density of the fluid~~by~~ from the difference in the effective sound
7 speeds as will be more fully described~~herein~~ below. Sound speed meters 14, 16 utilize
8 acoustic pressure signals that, as measured, are lower frequency (and longer wavelength)
9 signals than those used for ultrasonic flow meters of the prior art, ~~and thus as explained in~~
10 ~~the incorporated ‘094 application. Thus,~~ the current invention is more tolerant to
11 inhomogeneities in the flow. In addition, ~~the present invention differs from prior art fluid~~
12 ~~parameter measurement devices in that the present invention incorporates the compliance~~
13 ~~of the pipe to~~

14 ~~determine the effective speed of sound of the pipe/fluid system.~~ The typical
15 frequency range for acoustic pressure signals of the present invention is from about 10 Hz
16 to about 10,000 Hz. The acoustic pressure signals are generated within the fluid of the
17 pipe 12 by a variety of non-discrete sources such as remote machinery, pumps, valves,
18 elbows, as well as the fluid flow itself. It is this last source, the fluid flowing within the
19 pipe, that is a generic source of acoustic noise that assures a minimum level of acoustics
20 for any fluid-piping-pipe systems for which the present invention takes unique
21 advantage. The flow generated acoustics increase with mean flow velocity and the
22 overall noise levels (acoustic pressure levels) are a function of the generating mechanism
23 and the damping mechanism. Experience indicates that pipe systems typically have
24 sufficient ambient noise levels of 100 to 180 dbA.

25 No external discrete noise source is required within the present invention and thus
26 may operate using passive listening. It is within the scope of the present invention that the
27 sound speed meter or sensor 14, 16 spacing may be known or arbitrary and that as few as
28 two sensors are required if certain information is known about the acoustic properties of
29 the system as will be more fully described ~~herein~~ below.

30 ~~It is an important aspect of the present invention that one-dimensional, As is~~
31 ~~known and as is described in the references incorporated herein, planar compression~~

1 waves 30 propagating within a fluid contained within a conduit 12 exert an unsteady
2 internal pressure loading on the conduit. The degree to which the conduit displaces as a
3 result of the unsteady pressure loading influences the speed of propagation of the
4 compression wave 30 within the context of the fluid/pipe system. For a given fluid, the
5 more compliant the conduit, the greater the reduction of the propagation velocity of the
6 compression wave. Also, for a given pipe stiffness, the denser the fluid and the higher
7 the infinite volumedomain sound speed, i.e., the speed of sound in an unbounded media,
8 the greater the reduction in the speed of sound due to the pipe flexibility or compliance.

9 The compliance. More specifically, the relationship among between the infinite
10 domain speed of sound sound speed (a_{mix_∞}) and (a_{mix_0}), density (ρ_{mix}) of a fluid; fluid, the
11 elastic modulus of the pipe (E), thickness of the pipe (t), and the radius of a vacuum-
12 backed cylindrical conduit (R), and the effective propagation velocity (a_{eff}) for a one
13 dimensional compression wave is given by the following expression:

14

15

$$a_{eff} = \frac{1}{\sqrt{\frac{1}{a_{mix_\infty}^2} + \rho_{mix} \frac{2R}{Et}}} \quad \text{eq(Eq. 1)}$$

16 Figure Fig. 2 shows the effective propagation velocity, or effective system sound
17 speed for a specific example of the density meter 1 of Fig. 1 in accordance with the
18 present invention. In this particular embodiment, the effective system sound speed is
19 shown for a fluid contained in a vacuum-backed, cylindrical steel conduit with acoustic
20 propagation velocities and density representative of hydrocarbon liquid and water
21 mixtures as typically found in the oil and gas industry. Figure Fig. 2 shows the effect of
22 varying the compliance of the pipe/fluid system by changing the wall thickness of a 5.50
23 inch OD steel pipe from some theoretical minimum value to a thickness of 0.5 inches for
24 five different fluids having densities from 600 to 1000 kg/m³. As shown in Fig. 2,
25 varying the thickness of the pipe has a significant effect on the effective speed of sound
26 of the fluid/pipe system. For simplicity sake, the present invention is described with
27 regard to particular embodiments comprising vacuum-vacuum-backed conduits having
28 sufficiently low frequencies (compared to breathing mode and resonant frequencies) such
29 that the pertinent dynamical response is captured by the static compliance of the conduit.

1 The conduit may be vacuum backed by a concentric shell 15 (Fig. 1) or other suitable
2 structure to isolate the sensing regions X_1 , X_2 from the outside environment. In
3 alternative embodiments, the sensing regions X_1 , X_2 may be isolated within the
4 concentric shell 15 by a known fluid or air. It is important that a static fluid having lower
5 acoustic impedance than the fluid flowing within the pipe surround the sound speed
6 meters. The advantages and effect of the vacuum backed conduit, as well as other
7 isolation techniques, are described in ~~commonly owned copending U.S.~~ Patent
8 Application Serial No. 09/344,070, entitled "Measurement of Propagating Acoustic
9 Waves in Compliant Pipes" Pipes, filed June 25, 1999, which is incorporated herein by
10 reference in its entirety.

11 Equation 1 can be generalized in terms of the cross-sectional area compliance
12 ($\sigma_{conduit}$) of the conduit and the infinite sound speed ~~and speed~~, the density of the fluid, and
13 the effective sound speed of the ~~pipe / fluid~~ pipe/fluid system as given by:

14

$$15 \quad \frac{1}{\rho_{eff} a_{eff}^2} = \frac{1}{\rho_{mix} a_{mix_\infty}^2} + \sigma_{conduit} \quad (\text{eq. Eq. 2})$$

16

17 The cross sectional area compliance is a measure of the increase in cross-sectional
18 area of a conduit for a given increase in internal pressure as set forth in the following
19 relationship:

$$20 \quad \sigma_{conduit} = \frac{\partial A_{cross section}}{\partial P} \quad (\text{eq. Eq. 3})$$

21 For a vacuum-backed, circular cross-section pipe of elastic modulus E, having an
22 outside radius R, and wall thickness t, the conduit compliance is given by:

23

$$24 \quad \sigma_{conduit} = \frac{2R}{Et} \quad (\text{eq. Eq. 4})$$

25

26

27 It is important to note that, in general, the cross sectional area compliance of the
28 fluid/pipe system can be a complex function of frequency and amplitude and can depend

1 on all elements acoustically coupled to the conduit. For example, if an additional fluid
2 surrounded the conduit, the acoustic properties of the surrounding fluid would influence
3 the cross sectional area compliance presented to the compressional waves propagating
4 internal to the conduit. It is for this reason that the present invention is presented in
5 embodiments having a vacuum backed shell surrounding the sound speed meters as
6 describedherein above.

7 In accordance with the present invention, using the relationships describedherein
8 above, the dependence of propagation speed of compression disturbances (one
9 dimensional, planar compression acoustic waves) on the compliance of the conduit 12
10 and fluid properties(such as namely sound speed and density) can be used to determine
11 information regarding the fluid contained within the conduit, specifically, the density of
12 the fluid.

13 Referring again to ~~Figure~~Fig. 1, there is shown a density meter 1 in which the
14 speed of sound of an unknown fluid 13 is measured within two regions X_1 , X_2 ~~wherein~~
15 ~~the pipe~~ X_2 , and in which the pipe 12 has differing cross sectional area compliances
16 associated with the two regions. A first effective speed of sound a_{eff} of the fluid/pipe
17 system is determined from an array of pressure measurements provided by sensors of
18 sound speed meter 14. A second speed of sound a_{eff2} of the fluid/pipe system is
19 determined from an array of pressure measurements provided by sensors of sound speed
20 meter 16. As will be more fully describedherein below, the change in propagation
21 velocity of one dimensional acoustic waves between the two regions X_1 , X_2 , along with
22 knowledge of the cross sectional compliances of each section, provides a means to
23 determine the density of the fluid 13. As illustrated in this example, the variation in
24 thesystem cross sectional compliance could be achieved through a changeⁱⁿ the conduit
25 compliance, namely in the form ofe.g., through a change in wall thickness of the pipe.
26 Other methods to vary thesystem cross sectional area compliance are described below,
27 and any known method of varying thesystem cross sectional area compliance is
28 contemplated by the present invention.

29 The invention will now be described with attention to another specific
30 embodiment commonly found in the oil and gas industry with reference to Figs. 1 and 3
31 ~~wherein the system~~³, wherein varying the fluid compliance varies the cross sectional

1 compliance is varied by varying the fluid area compliance. In this exemplary embodiment
2 the pipe 12 is comprised of a single material type, Inconel for example, have a wall
3 thickness t_1 at region X_1 of 0.10 inches and a wall thickness of t_2 at region X_2 of 0.35
4 inches. The pipe is vacuum ~~mandrel~~-backed with a shell 15 isolating that isolates the
5 sound speed meters from the outside environment. As best shown in Fig. 3, the change in
6 sound speed for fluid mixtures, such as representative hydrocarbon and water mixtures,
7 having densities ranging from 600 to 1000 kg/m³, is quite dramatic. As shown, the
8 change in sound speed scales with the acoustic impedance of the fluid. For the least
9 dense fluid with the slowest infinite medium sound speed (representing a light
10 hydrocarbon), the change in wall thickness results in approximately 300 ft/sec change in
11 sound speed. For the densest, highest infinite medium sound speed (representing, for
12 example, a high watercut mixture)-, the change in wall thickness results in a 750 ft/sec
13 change in sound speed. The expression for the change in effective speed of sound
14 between two sections of ~~vacuum-backed~~ conduit differing only in wall thickness, where
15 a_o is the speed of sound of the fluid and ρ_o is the density of the fluid is given by:

16

$$17 \quad a_{eff_1} - a_{eff_2} = \frac{1}{\sqrt{\frac{1}{a_o^2} + \rho_o \frac{2R}{Et_1}}} - \frac{1}{\sqrt{\frac{1}{a_o^2} + \rho_o \frac{2R}{Et_2}}} \quad (\text{Eq. 5})$$

18

19 In accordance with the present invention, the density of the unknown fluid is determined
20 by measuring two effective system sound speeds in two regions with differing, but known
21 structural properties. For example, in the cylindrical pipe 12 of Fig. 1, having a thickness
22 t_1 and t_2 and elastic modulus E, the density ρ_{mix} of the unknown fluid is given by:

23

$$24 \quad \rho_{mix} = \left(\frac{1}{a_{eff_1}^2} - \frac{1}{a_{eff_2}^2} \right) \frac{E}{2R} \frac{t_1 t_2}{t_2 - t_1} \quad (\text{eq(Eq. 6)})$$

25

26 As discussed herein noted above, varying wall thickness is but one way to achieve
27 a change in system cross sectional area compliance and thereby provide a density

1 ~~measurement~~compliance, and accordingly to measure fluid density in accordance with
2 the present invention. In general, the larger the change insystem cross sectional area
3 compliance between the two (or more) regions in which the sound speed is measured,
4 the more robust the density measurement. In addition, an increase in the number of
5 regions, i.e. greater than two, along a pipe with varying compliance in whichsystem
6 sound speeds are measured would give additional, redundant measurements of density.
7 The additional data could yield a more robust or accurate overall system depending on
8 the specific application.

9 One alternative method to achieve large variations insystem compliance by
10 changing the conduit compliance is best shown with reference to Fig. 4 wherein a first
11 sensing region in surrounding X₁ comprises a circular cross section conduit andsectional
12 conduit while a second sensing region in surrounding X₂ comprises a non-circular
13 cross section conduit, shownsectional conduit (shown as an egg-shaped conduit by way of
14 example, allexample). All other properties of the pipe remainingpipe remain equal. The
15 circular geometry surrounding at X₁ represents, for a given cross section, material
16 modulus, and wall thickness, the configuration with the lowest cross sectional area
17 compliance. However, the geometry of the cross section of the modified sensing region
18 surrounding X₂, such as at X₂, formed by modifying or “egging” the circular section into
19 an oval (or other alternative shapes such as using a cross section possessing flattened
20 sides) significantly increases the compliance of the conduit 12. In certain embodiments
21 between sensing region X₂ (non-circular geometry) and sensing region X₁ (circular
22 geometry) of the same wall thickness t, cross sectional area compliance ratios greater
23 than 30 are achievable. As demonstrated in the figures referenced herein above,
24 increasing the compliance ratio of the pipe section increases the sensitivity of the density
25 meter 1calculation by increasing thesystem compliance ratio thereby increasing the
26 change in effectivesystem sound speed for a given fluid density.

27 The effectivesystem cross sectional area compliance can be modified in a variety
28 of manners such as, by way of example, by varying materials, by incorporating wall
29 treatments, or by incorporating resonators or cavities. Referring to Fig. 5, there is shown
30 a modifiedsystem cross sectional area compliance technique wherein a closed cell foam
31 70 (or other compressible liner material) is positioned along the walls of one of the

1 sensing sections of the pipe 12 thereby modifying to modify the effective compliance of
2 that section of pipe. In the embodiment shown in Fig. 5, the pipe / fluidpipe/fluid
3 interface would be defined as the inner surface of the liner. An increase in fluid pressure
4 would increase the effective cross sectional area of the fluid by both compressing the
5 foam and by expanding the pipe. It is also contemplated by the present invention that the
6 two sensing regions may be comprised of different material types or any other variation
7 in geometry or material property that would effectuate a difference in the compliance of
8 the pipe between the two sensing regions.

9 In another example of the present invention, varying the compliance of the fluid
10 or the area within the pipe can vary the system cross sectional area compliance. For
11 instance, and referring to Fig. 6, additional system compliance could be introduced at a
12 location along the pipe by positioning a tube 72 within the flow path along one of the
13 sensing regions. The tube 72 would serve to modify the cross sectional compliance by
14 compressing due to an increase in fluid pressure and pressure, which would then combine
15 with the compliance of the pipe to modify the effective sound speed of the fluid/pipe
16 system. Other alternatives include embodiments wherein the tube is an air filled, sealed
17 tube (or tubes) positioned within one sensing region of the pipe.

18 Referring again to Fig. 1, and defining α as the ratio of conduit compliance in the
19 “soft” section, sensing region X_1 , of the density meter 1 to that of the “stiff” section,
20 sensing region X_2 , of the meter, section (X_1) to the “stiff” section (X_2) and where σ_2 is
21 the cross sectional area compliance of sensing region X_2 of the meter, the density of the
22 fluid ρ_{mix} within the meter can be expressed as:

23

24

$$\rho_{mix} = \frac{1}{(\alpha - 1)\sigma_2} \left(\frac{1}{a_{eff_1}^2} - \frac{1}{a_{eff_2}^2} \right) \quad (\text{eq(Eq. 7)})$$

25

26

27 Referring now to Figure 7Fig. 7, there is shown the speed of soundfluid sound
28 speed of a varying mixture of a two part brine/water fluid as measured in two sensing
29 regions X_1 , X_2 , of an embodiment of density meter 1 of Fig. 1. The figure shows the

1 various effective sound speeds versus oil volume fractions for oil/water mixtures varying
2 from 0% oil to 100% oil by volume. In the example shown, the two sensing sections
3 have a compliance ratio α of 10. As shown in Fig. 7, the difference in measured sound
4 speed between the two sections varies from approximately 400 m/s for 100% brine,water,
5 to approximately 200 m/s for 100% oil. As described herein above and depicted in the
6 figure, the effective system speed of sound as measured in the stiff section (X_2) is
7 significantly higher for the mixture than that measured in the less stiff soft section (X_1) of
8 the pipe 12.

9 In operation and referring again to Fig. 1, the two sound speed meters 14, 16
10 provide effective system sound speeds $a_{1\text{eff}}$ and $a_{2\text{eff}}$ to signal processing logic 60, which
11 includes the relationship set forth in equation 7. The compliance of the conduit σ_2 in the
12 second sensing region X_2 and the ratio of the compliances between the two sections σ_1/σ_2
13 are further provided to logic 60 to calculate the density of the mixture, ρ_{mix} . It is an
14 important aspect of the present invention that Thus the density of the fluid mixture can be
15 determined without requiring specific speed of sound and calibration information
16 concerning the fluid itself. In the embodiments described thus far, it is only required
17 that the infinite sound speed (a_{mix}) and density of the fluid itself is the same in the two
18 sections. Thus, although the density measurement described herein is based on speed of
19 sound measurements, no knowledge of the infinite sound speed (a_{mix}) of the fluid is
20 required to determine density.

21 In certain other embodiments, the density of the fluid may be determined after the
22 introduction of a known quantity of a known constituent into the fluid between the two
23 sensing sections. Referring to Fig. 8, there is shown a density meter 1 including an input
24 line 74 positioned between the two sensing sections X_1 , X_2 . In this particular
25 embodiment the system cross sectional area compliance is changed by the introduction of
26 a constant amount of a known quantity of air 75, for example, into the fluid 13. The
27 introduction of the air into the fluid changes the system cross section cross-sectional area
28 compliance in the sensing region (X_2) downstream of input line 74. The change in
29 compliance in the fluid due to the introduction of the air is taken into account in the
30 relationships described herein above to accurately determine the density of the fluid 13.

1 In addition to liquid mixtures, the density meter of the present invention includes
2 the ability to determine the density of ~~gas / liquid~~gas/liquid mixtures. Referring to ~~Figure~~
3 ~~9~~Fig. 9, there is shown the predicted sound speeds in the stiff (X_2) and soft (X_1) sensing
4 regions of density meter 1 depicted in ~~in~~ Fig. 1 for various mixtures of gas and liquids
5 with representative single phase compliances typical of produced gases and liquids at 100
6 bar. As shown, due primarily to the high compliance of the gas phase at this relatively
7 low pressure, the change in overall sound speed in the two sections of the meter due to
8 the change in conduit compliance is much less significant for this application than those
9 described above. ~~From~~Using Equation 2, and ~~by~~ defining the compliance of the fluid as
10 the inverse of the product of the fluid density and the square of the infinite dimensional
11 sound speed ~~yields~~yieldsspeed, the following relation ~~results~~:
12

$$13 \quad \sigma_{mixture} \equiv \frac{1}{\rho_{mix} a_{mix_\infty}^2} \quad (\text{Eq. 8})$$

14 and the ratio of the effective sound speed within the conduit to the infinite dimensional
15 sound speed is given by:

$$16 \quad \frac{a_{eff}}{a_{mix_\infty}} = \sqrt{\frac{1}{1 + \frac{\sigma_{conduit}}{\sigma_{mixture}}}} \quad (\text{Eq. 9})$$

17 The change in difference in sound speed for a given change in density of the fluid
18 is a useful metric in designing the density meter described ~~herein~~ for any specific
19 application. Assuming that the ratio of the cross sectional compliance introduced by the
20 structure over that of the fluid is much less than 1, this performance metric can be
21 expressed as follows:
22

$$23 \quad \frac{\partial(a_{1_{eff}} - a_{2_{eff}})}{\partial \rho} = \frac{a_{mix_\infty}}{\rho_{mix}} \frac{\sigma_{Stiff}}{\sigma_{mixture}} \frac{1}{2}(\alpha - 1) \quad (\text{Eq. 10})$$

24
25 As shown, effectiveness of the density meter of the present invention described ~~herein~~
26 scales with both the ratio of the compliances of the two conduits as well as with the ratio
27 of the compliance of conduit to that of the fluid. Thus, the density meter of the present

1 invention is more effective when the system cross sectional area compliance contributed
2 by the conduit is a significant fraction of that contributed by the fluid and the ratio of
3 the system cross sectional area compliance of the two regions is significantly greater than
4 one.

5 It should be understood that any of the features, characteristics, alternatives or
6 modifications described regarding a particular embodiment herein may also be applied,
7 used, or incorporated with any other embodiment described herein.

8 Although the invention has been described and illustrated with respect to
9 exemplary embodiments thereof, the foregoing and various other additions and omissions
10 may be made therein and thereto without departing from the spirit and scope of the
11 present invention.

12



Abstract of the Disclosure

3 The density of at least one fluid in a pipe 12 is determined using a pair of
4 effective sound speeds $a_{1\text{eff}}$ and $a_{2\text{eff}}$ of the fluid/pipe system. The pair of effective system
5 sound speed measurements are taken at two sensing regions X_1, X_2 along the pipe
6 wherein each of the sensing regions comprises has a different system cross sectional area
7 compliance. The pair of effective system sound speeds $a_{1\text{eff}}$ and $a_{2\text{eff}}$ are is provided to
8 signal processing logic 60, which determines the density of the fluid 13 flowing in the
9 pipe 12. The effective system sound speeds $a_{1\text{eff}}$ and $a_{2\text{eff}}$ ~~may~~ $a_{2\text{eff}}$ may be provided by a
10 pair of sound speed meters positioned at the sensing regions X_1, X_2 wherein the sound
11 speed meters utilize a spatial array of acoustic pressure sensors placed at predetermined
12 axial locations along the pipe 12. The acoustic pressure sensors provide acoustic pressure
13 signals which determine the effective system speed of sound $a_{1\text{eff}}$ and $a_{2\text{eff}}$ of the fluid (or
14 mixture)/pipe system. One technique uses acoustic spatial array signal processing
15 techniques with the direction of propagation of the acoustic signals along the longitudinal
16 axis of the pipe 12. However, numerous spatial array processing techniques may be
17 employed to determine the effective system speed of sounds $a_{1\text{eff}}$ and $a_{2\text{eff}}$. The effective
18 system sound speeds $a_{1\text{eff}}$ and $a_{2\text{eff}}$ measured utilize measure one-dimensional planar
19 acoustic waves that are lower in frequency (and longer wavelength) signals than those
20 used for ultrasonic flow meters, and thus incorporates pipe compliance with fluid
21 compliance and further is more tolerant to inhomogeneities in the flow. In addition, no
22 external acoustic source is required and thus the meters may operate using passive
23 listening. The invention will work with arbitrary sound speed meter spacing and with as
24 few as two sound speed meters.

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